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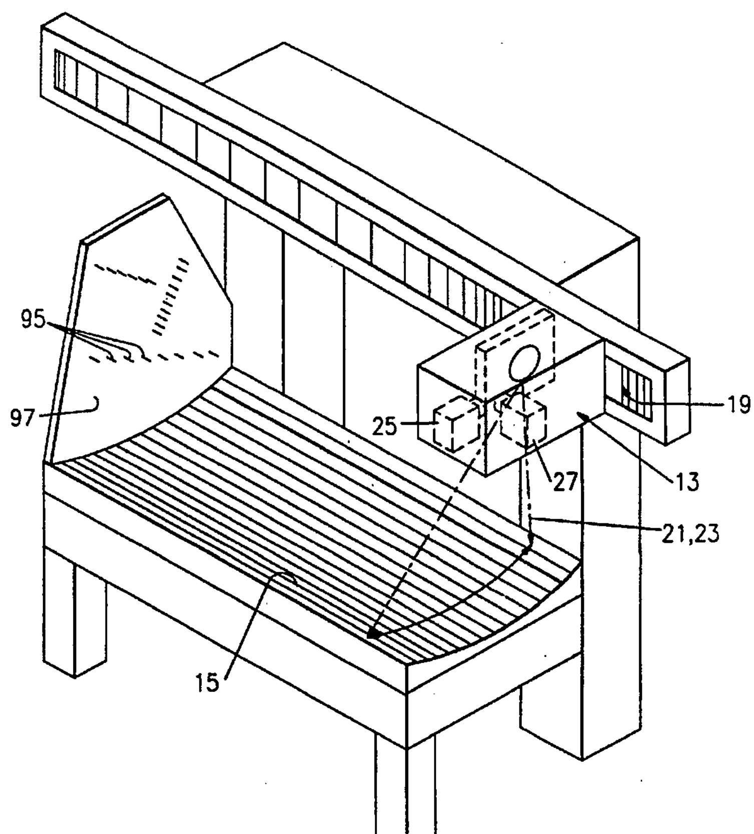
(57) Abstract

The present invention provides an improved apparatus, and method, for precision scanning of an article such as a bent pipe located in a measurement volume, to map the pipe's exterior surface in three dimensions. The apparatus scans the measurement volume using an intensity-modulated laser beam and compares the phase of a detected return beam with the phase of the incident beam to the determine range. A second scanning of the measurment volume resolves range ambiguities so that a precise three-dimensional mapping can be achieved.



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METHOD AND APPARATUS FOR PRECISION INSPECTION OF ARTICLES

BACKGROUND OF THE INVENTION

This invention relates generally to systems for inspecting articles such as pipes or tubes bent into complex shapes and, more particularly, to systems of this kind that map the articles' surface characteristics in three dimensions.

Apparatus of this particular kind are useful in numerous applications. For example, such apparatus can be used to inspect manufactured articles to verify that they have been formed into the desired three-dimensional shape. Such apparatus also are useful in reverse-engineering applications, where the three-dimensional shape of an article is to be determined for purposes of subsequent duplication. Further, such apparatus are useful as part of a real-time manufacturing system that requires monitoring of an article as it is being shaped.

In the past, apparatus of this kind have included coordinate measuring machines of the kind having a stylus supported on an articulated arm that can be moved sequentially by an operator to specific sites on the article, to determine their coordinates in three-dimensions. Although such machines have functioned generally effectively, they are considered unduly slow to obtain accurate coordinate data, especially when the article has a relatively complex shape. Such machines also suffer the drawback of requiring substantial operator involvement.

In the case of inspection apparatus for inspecting pipes or tubes bent into complex shapes, apparatus have been developed having probes for measuring the vectors of straight sections of the bent pipe so that a full three-dimensional map of the pipe can be calculated. Some of such apparatus have included optical probes that eliminate the need to physically contact the bent pipe with the probe.

Even so, such apparatus generally require substantial operator involvement, and substantial time is required to fully characterize the pipes' three-dimensional shapes. Further, such apparatus are not directly capable of determining the three-dimensional shapes of articles formed other than of straight vector sections.

It should therefore be appreciated that there is need for an apparatus and related method for inspecting articles, which can characterize the three-dimensional shape of the article's exterior surface rapidly and without the need for physically contacting the article and without the need for direct operator involvement. The present invention fulfills this need.

SUMMARY OF THE INVENTION

This invention is embodied in an apparatus, and related method, for scanning an article and rapidly providing a three-dimensional mapping of the article's exterior surface without the need for physically contacting the article and without requiring direct operator involvement. More particularly, the article is placed within a measurement volume, and the apparatus scans the article with an intensity-modulated beam of coherent radiation, e.g., a laser beam, to produce a reflected beam. The intensity of the reflected beam is detected to generate a detection signal, and the phase of this detection signal is compared with the phase of the original modulation signal to produce a first phase difference signal. The beam is then intensity modulated by a second modulation signal and again scanned across the article to produce a reflected beam. The reflected beam is detected and compared in phase with the second modulation signal, to generate a second phase difference signal. A processor then processes the first and second phase difference signals to determine the article's three-dimensional shape.

In an optional, more detailed feature of the invention, the first and second modulation signals are sine waves, of differing frequencies, and the entire measurement volume is scanned by the beam modulated by the first modulation signal, before the volume is scanned by the beam modulated by the second modulation signal. The initial scanning is performed at a coarse resolution, and the second scanning at a fine resolution.

In another optional feature of the invention, a plurality of calibration objects are located within the measurement volume, each having a known position in three-dimensions. The processor calibrates the first and second phase difference signals based on the portions of such signals that are derived from scanning the modulated beam across the calibration objects. The calibration objects can take the form of pins attached to predetermined locations on an end wall of that defines the measurement volume. The calibration objects can be scanned after the initial, coarse-resolution scan of the article and before the second, fine-resolution scan of the article.

In yet another optional feature of the invention, the modulation signal is phase-delayed by a predetermined amount, e.g., 90 degrees, and the phases of both the original modulation signal and the phase-delayed modulation signal are compared with the phase of the detection signal. One of the two resulting signals is selected to be the phase difference signal, with the selection being made to provide the best resolution. The processor also can utilize the detection signal itself, as well as the first and second phase difference signals, to map the article's three-dimensional shape.

Other features and advantages of the present invention should become apparent from the following description with the preferred embodiment, taken in

conjunction with the accompanying drawings, which illustrate, by way of example, the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of an optical inspection apparatus in accordance with the preferred embodiment of the invention, for optically inspecting an article such as a bent pipe and mapping the article's surface geometry in three-dimensions.

FIG. 2 is a schematic end view of the apparatus of FIG. 1, shown with a bent pipe in position to be scanned.

FIG 3 is a block diagram of the signal processing portion of the apparatus of FIG. 1.

FIG. 4 is a graph showing the relationship between the first and second phase error signals and the height of the article being scanned.

FIGS 5(a) and 5(b) are graphs of the detection signal and height determination for one particular scan made by the apparatus of FIG. 1.

FIG. 6 is a simplified flowchart showing the operational steps performed by the apparatus of FIG. 1, in scanning the article.

FIG. 7 is an exploded perspective view of one of numerous calibration pins used for calibrating the scan.

DESCRIPTION OF THE PREFERRED EMBODIMENT

With reference now to the drawings, and particularly to FIGS. 1 and 2, there is shown an apparatus

for optically inspecting and mapping the three-dimensional shape of an article such as a pipe 11 bent into a complex three-dimensional shape. The apparatus includes a scanning head 13 configured to scan a predetermined volume defined by a concave measurement bed 15 in a raster-scan fashion. The scanning head directs an intensity-modulated laser beam onto a rotating polygonal mirror 17, to scan the beam repeatedly across the bed. In addition, a transport mechanism 19 moves the scanning head longitudinally above the bed, from one end to the other. In this fashion, a raster scan is provided. The transport mechanism can take the form of a linear positioning stage such as an Anoguide stage manufactured by Anorad Corporation, of Hauppauge, New York. For each pixel of the raster scan, the apparatus measures the article's elevation above the bed, whereby the pipe's precise three-dimensional shape can be ascertained.

The scanning head 13 projects the intensity-modulated beam 21 downwardly toward the pipe 11 and the measurement bed 15. A portion of the resulting reflected light forms a reflected beam 23 that is directed back toward the scanning head. A data channel photodetector 25 (FIG. 3) on the head detects the instantaneous intensity of this reflected beam and produces a corresponding data channel or detection signal. Simultaneously, a portion of the incident beam is directed to a reference channel photodetector 27 (FIG. 3) on the head, which detects its instantaneous intensity and produces a corresponding reference channel signal. Both photodetectors preferably are quantum photodetectors.

A phase detector 29 (FIG. 3) compares the phases of the data channel signal and the reference channel signal, to produce a phase difference signal indicative of the range from the scanning head 13 to the incident beam's point of impingement on the pipe 11 or the bed 15. A separate such phase difference signal is produced for each pixel as the

scanning head completes its raster scan of the measurement bed. This enables the pipe's surface geometry to be precision mapped in three-dimensions.

With reference now to FIG. 3, there is shown a block diagram of the signal processing portion of the inspection apparatus of FIG. 1. The laser beam 21 is produced by a laser diode 31 under the control of a modulation frequency selector 33, which controllably adjusts the power delivered to the laser diode according to a selected one of two predetermined frequency signals. The two frequency signals are supplied from separate crystal oscillators 35 and 37, which in the preferred embodiment operate at 320 MHz and 400 MHz. The beam's intensity is made to vary sinusoidally between substantially zero and a predetermined maximum, in accordance with the selected frequency signal.

The beam emitted by the laser diode 31 is directed to a beam splitter 39, which transmits a small portion of the beam to the reference channel photodetector 27. This produces the reference channel signal, which is output on line 41. The remaining portion of the incident beam 21 is reflected by the beam splitter to the rotating polygonal mirror 17, which is configured to repeatedly scan the beam across the measurement bed 15. A portion of the scanning beam is reflected to form the reflected beam 23 that is directed back to the scanning head 13, where it is redirected by the rotating polygonal mirror to the data channel photodetector 25. This produces the data channel signal, whose intensity varies according to the instantaneous intensity of the reflected beam. The data channel signal is output on line 43.

The difference between the phase angles of the data channel signal and the reference channel signal indicates the round-trip time delay of the incident beam 21

and the reflected beam 23. This time delay, of course, varies according to the relative position of the beam's point of impingement on the pipe 11 or underlying bed 15.

The measurement bed 15 has a cylindrically concave surface configured such that the scanning incident beam 21 always impinges on it substantially perpendicularly. The bed preferably formed of stainless steel or a composite material such as Anocast. The reflected beam 23 therefore has a relatively high intensity, and it is directed back toward the scanning head 13, for detection by the data channel photodetector 25. In addition, the round-trip time delay is substantially the same for all points of impingement of the bed. When the incident beam impinges on a portion of the pipe 11 positioned on the measurement bed, most of that beam is reflected laterally away, except when portions of the pipe aligned with the pipe centerline are being scanned, in which case the beam is reflected generally back toward the scanning head. Usually, enough of the incident beam is reflected back toward scanning head to allow a phase error measurement to be made across the entire upper surface of the pipe.

The system further includes frequency down converters 45 and 47 for translating down in frequency the respective data channel signal on line 43 and reference channel signal on line 41. Also supplied to the frequency down converters is a local oscillator frequency signal on line 49 from a frequency selector 50. The frequency selector selects a signal from either a 310-MHz local oscillator 50 or a 390-MHz local oscillator 52, depending on the frequency selection concurrently being made by the frequency selector 33. The resulting down-converted signal therefore has a frequency of 10 MHz. A second preferred embodiment utilizes local oscillator frequencies that yield a down-converted frequency 2 MHz.

The phase detector 29 receives the down-converted data channel signal on line 53 and the reference channel signal on line 55 from the down converters 45 and 47, respectively, to produce a signal whose value corresponds to their instantaneous phase difference. As mentioned above, this phase difference indicates the round trip time delay experienced by the incident beam 21 and the reflected beam 23, which of course varies in accordance with the relative height of the incident beam's point of impingement on either the pipe 11 or the underlying measurement bed 15.

The phase difference signal output by the phase detector 29 on line 57 varies triangularly between a maximum value if the two input signals are precisely in phase and a minimum value if the two input signals are precisely 180° out of phase. Maximum resolution therefore occurs in the region where the two signals are approximately 90° out of phase with each other, and only limited resolution occurs where the two signals differ in phase by about 0° or 180°. This phase difference signal is shown in FIG. 4, identified by the reference letter A.

To provide improved resolution in regions where the phase angles of the two down-converted signals differ by amounts near 0° or 180°, the apparatus further includes a 90° phase shifter 59 and a second phase detector 61. The 90° phase shifter delays the down-converted reference channel signal, received on line 55, and the second phase detector compares the phase angle of the delayed signal, which is received on line 63, with that of the down-converted data channel signal received on line 53. The resulting phase difference signal output on line 65 by this second phase detector is designated by the reference letter B in FIG. 4, along with the phase difference signal output on line 57 by the first phase detector 29. It will be appreciated that at least one of the two signals always is relatively near its mid-point value, where measurement

precision is optimized.

The phase difference signals output by the phase detectors 29 and 61 are supplied on lines 57 and 65, respectively, to first and second analog-to-digital (A/D) converters 67 and 69, respectively. Each A/D converter generates a sequence of 14-bit digital words, each such word constituting the data for one pixel of the raster scan. The A/D sample rate preferably is on the order of 2 MHz and is synchronized with rotation of the polygonal mirror 17 and with translation of the transport mechanism 19. The precise location of each sample relative to the measurement therefore is known.

The digital word sequences are supplied on lines 71 and 73 from the respective first and second A/D converters 67 and 69 to a channel selector 75, which selects the particular one of the two sequences whose value is closest to the mid-point value. As mentioned above, this means that the selection provides the particular digitized phase difference signal that provides the better accuracy. In FIG. 4, the selected phase difference signal is depicted by the bold line. Thus, for example, if the two phase difference signal values for a particular pixel are the values indicated by the reference line 77 in FIG. 4, then the channel selector 75 will select the channel B signal.

The selected digitized phase difference signal is transmitted on line 79 from the channel selector to a multiplexer 81 and, in turn, on line 83 to a computer 85, for interim storage and further processing. In the preferred embodiment, the computer is an Intel i860 microprocessor.

To provide additional information about the location of the pipe 11 on the measurement bed 15, the apparatus further is adapted to measure the intensity of the

reflected beam 23 for each pixel in the raster scan. This facilitates a detection of the portion of the pipe aligned with the pipe centerline. With reference to FIGS. 5(a) and (b), it will be noted that the range value, as indicated by the phase difference measurement of FIG 5(a), varies only slightly on opposite sides of the pipe's top-dead center, while the raw intensity value, as indicated by the intensity measurement of FIG. 5(b), varies quite substantially. The intensity measurement, therefore, is a good indicator of the pipe's precise top-dead center location, and the measurement is specifically used for that purpose.

The apparatus therefore includes a low-pass filter 87 for monitoring the down-converted data channel signal present on line 43. The filter's bandwidth is selected to substantially eliminate signal variations resulting from the intensity modulation, but to pass sufficient frequencies to enable the edges of the pipe to be conveniently detected. The filtered signal is transmitted on line 89 to an A/D converter 91, for digitizing, and in turn on line 93 to the multiplexer 81. The multiplexer selectively loads the digitized words into the computer 85, for further processing along with the phase difference data.

The apparatus is configured to provide a measurement accuracy equal to, or better than, plus or minus .005 inches, in all three dimensions. Using readily available phase detectors, which generally provide a resolution of only about .1°, this requires the modulation frequency to exceed about 300 MHz in order to achieve the desired ranging accuracy. The length and width accuracies are controlled by the precision and repeatability characteristics of the transport mechanism 19 and the rotational velocity stability of the rotating polygonal mirror 17 and its associated drive motor. Unfortunately, at this modulation frequency, several complete wavelengths of the intensity-modulated beam occupy the height region of

interest. Thus, multiple elevations within the measurement volume will yield the same detected phase difference.

The apparatus resolves this measurement ambiguity by causing the scanning head 13 to scan the measurement volume in two successive passes, each using a different modulation frequency. In an initial pass, the measurement volume is scanned at a relatively high speed, such that coarse measurement data is obtained. Thereafter, the measurement volume is scanned again at a relatively low speed, such that fine measurement data is collected. As is discussed in greater detail below, the computer 85 overlays the coarse data with the fine data, to resolve the measurement ambiguities and provide a precise mapping of the pipe's vertical profile.

Calibration of the apparatus is achieved using a number of calibration pins 95 mounted at predetermined locations on an end wall 97 of the measurement volume. These pins are shown in FIGS. 2 and 7. The pins project into the measurement volume, and the scanning head 13 scans the modulated laser beam 21 across the pins at the end of its coarse scanning of the measurement volume and again at the beginning of its fine scanning of the measurement volume.

About 32 calibration pins 95 are provided, and they are positioned at varying heights on the end wall 97, at one-inch intervals. A special geometric pattern is selected so that the upper pins do not obscure the lower pins and so that all 32 pins are visible to the scanning head 13. To improve precision, the pins are scanned about 100 times between the coarse and fine scans, and the resulting phase angle measurements are averaged to provide a single precision measurement for each pin.

The upper side of each calibration pin 95, which

is the side scanned by the incident beam 21, is flat and oriented substantially perpendicular to the incident beam. A substantially uniform height for each pin thereby is provided. The pins are placed in bores formed in the end wall 95 and tightened in place by nuts 99 (FIG. 7) located on the wall's opposite side.

FIG. 6 is a simplified flowchart of the operating sequence followed by the inspection apparatus in mapping the pipe's three-dimensional shape. In an initial step 101, the apparatus is energized and run through a conventional self-test procedure, in which various electrical parameters are measured and compared with desired values. Thereafter, in step 103, the lower modulation frequency (320 MHz) is selected by the modulation frequency selector 33 and the polygonal mirror 17 is made to rotate at a 20 Hz rate. In addition, the carriage 19 for transporting the scanning head 13 is operated at a relatively high speed. Under these operating conditions, the scanning head, in step 105, scans the measurement volume to accumulate coarse measurement data and form a low-resolution image of the pipe 11, and stores this accumulated data in the computer 85.

Thereafter, in step 107 the apparatus reconfigures itself for calibration by reducing the polygonal mirror's rotation rate to 10 Hz and by stopping the translation via the carriage 19. Still in step 107, the apparatus scans the calibration pins 95 100 times, while the incident beam 21 remains intensity-modulated at the relatively low frequency of 320 MHz. Several measurement samples are made for each pin during each of the 100 scans. Immediately thereafter, but still in step 107, the pins are again scanned 100 times, while the beam is intensity-modulated at the relatively high frequency of 400 MHz. The calibration data accumulated during this step is then stored in the computer 85.

After the calibration scanning has been completed,

the apparatus in step 109 selects the 400 MHz modulation frequency and conditions the carriage 19 to translate the scanning head 13 at a relatively slow speed back along the measurement volume. The apparatus also conditions the polygonal mirror 17 to rotate at its relatively low rotation rate of 10 Hz. High-resolution scan data representing both phase angle and intensity is then accumulated for the entire measurement volume, and this data is stored in the computer, in step 111. It will, of course, be appreciated that alternatively, the high-resolution data could be accumulated first and the low-resolution data accumulated last.

In making the return pass of the scanning head 13 above the measurement bed 15, it will be appreciated that its translation speed can be increased to a maximum value while moving across any end regions of the bed to which the bent pipe 11 does not extend, as determined in the first pass. This minimizes the time required for a complete scan of the pipe. It will also be appreciated that by stepping the scanner head along the measurement volume, one can take multiple scans along each scan line and then average the values for each pixel, to reduce the magnitude of the one-sigma gaussian noise envelope. In addition, both high- and low-resolution scan data can be obtained during the time each line is being scanned. The calibration scan is accomplished at the completion of scanning the entire measurement volume.

After scanning has been completed, the computer 85, in steps 113 and 115, processes the stored low-resolution and high-resolution data along with the calibration data, to determine the measured range for each pixel in the raster scan array. In particular, the accumulated calibration data is processed to produce a pair of phase angle measurements for each of the 32 calibration pins 95, one for the low-frequency scan and the other for

the high-frequency scan. Pixel values for edge regions of each calibration pin are first discarded. The accumulated low-frequency and high-frequency scan images are overlayed to produce an ordered data pair for each pixel of the fine-resolution raster. Since the low-frequency scan data includes many fewer pixels than the high-frequency scan data, the low resolution pixel closest to each high resolution pixel being considered is used for generating the ordered pair for that pixel.

As mentioned earlier, multiple elevations or range values within the measurement volume will provide the same phase difference measurement. The resulting ambiguity in assigning a range value for a particular high-frequency (i.e., fine resolution) phase difference measurement is resolved with reference to the low-frequency (i.e., coarse resolution) phase difference measurement for the same pixel. In particular, for each of the five or so possible range values that correspond to a particular fine resolution phase difference measurement, the value of the expected coarse resolution phase difference measurement is calculated. The calculation is made based on the two modulation frequencies and determinable phase delays in the optics and electronics. The five calculated coarse measurements are compared with the actual coarse measurement, and the range value that corresponds to the calculated measurement closest to the actual coarse measurement is selected.

The precise range value for that pixel then is determined by interpolating the fine phase difference measurement with respect to the averaged phase difference measurements for the nearest calibration pins 95. By way of example, if the fine phase difference measurement for a particular pixel is 34.7°, and if the averaged phase difference measurements for the two nearest calibration pins are 30.7° and 38.7°, then it is determined that the pipe's elevation at the site of that pixel is precisely midway

between those two calibration pins. If the two pins are known to be 8.000 and 9.000 inches above the measurement bed 15, then that portion of the pipe is determined to have an elevation of 8.500 inches.

Subsequently, in step 117, the range determinations for the entire measurement volume are transformed from cylindrical coordinates into a more conventional cartesian coordinate system. The data then is digitally filtered in step 117 to remove spurious noise, as best can be determined. This can be accomplished, for example, by comparing the range value determined for each pixel with the range values determined for neighboring pixels and adjusting the range value if it deviates excessively from the others.

The final set of data thus characterizes the bent pipe 11 in three dimensions. To facilitate further processing, the data can be loaded into a computer-aided design (CAD) system, which allows the data to be analyzed and represented in a convenient, recognized manner. The accumulated data present in the CAD system is useful in numerous applications, including for example the mere inspection of a manufactured article's shape, as in the pipe inspection apparatus described specifically above. Another suitable application is the inspection of a damaged article for purposes of reverse engineering and duplication. Yet other applications include the inspection of an article when duplicating the article as part of an automated manufacturing system and in a stereolithography manufacturing system.

It should be appreciated from the foregoing description that the present invention provides an improved apparatus for precision scanning of an article such as a bent pipe located in a measurement volume, to map the pipe in three dimensions. The apparatus scans the measurement volume using an intensity-modulated laser beam and compares

the phase of a detected return beam with the phase of the incident beam to the determine range. A second scanning of the measurement volume resolves range ambiguities so that a precise three-dimensional mapping can be achieved.

Although the invention has been described in detail with reference only to the preferred embodiment, those of ordinary skill in the art will appreciate that various modifications can be made without departing from the invention. Accordingly, the invention is defined only by the following claims.

1. A method for determining the three-dimensional shape of an article located within a measurement volume, comprising the steps of:

modulating the intensity of a beam of coherent radiation in accordance with a first modulation signal;

scanning the modulated beam across an article located within a measurement volume such that the beam is reflected from the article to produce a reflected beam;

detecting the intensity of the reflected beam to generate a detection signal;

comparing the phase of the detection signal with the phase of the first modulation signal and generating a first phase difference signal;

modulating the intensity of the beam of coherent radiation in accordance with a second modulation signal and repeating the steps of scanning, detecting and comparing, to generate a second phase difference signal; and

processing the first and second phase difference signals to determine the three-dimensional shape of the article's exterior surface.

2. A method as defined in claim 1, wherein:

the first modulation signal is a sine wave having a first frequency; and

the second modulation signal is a sine wave having a second frequency.

3. A method as defined in claim 1, wherein:

the steps of modulating, scanning, detecting and comparing are completed before the step of modulating and repeating is initiated;

the initial step of scanning is performed at a first, coarse resolution; and

the step of scanning performed during the step of modulating and repeating is at a second, fine resolution.

4. A method as defined in claim 1, wherein:

the step of scanning scans the modulated beam in two dimensions across the entire measurement volume; and

the step of processing includes a step of determining the position of the article along the axis of the modulated beam for substantially the entire two-dimensional region that is scanned.

5. A method as defined in claim 4, wherein:

the measurement volume being scanned in the step of scanning is stationary; and

the step of scanning includes the steps of

scanning the modulated beam along a first direction using a movable mirror, and

moving the mirror in a second direction relative to the measurement volume, such that a raster scan of the measurement volume is achieved.

6. A method as defined in claim 1, wherein:

a plurality of calibration objects are located within the measurement volume, the calibration objects having known positions in three dimensions; and

the step of processing includes a step of calibrating the first and second phase difference signals based on the portions of such signals that are derived from scanning the modulated beam across the calibration objects.

7. A method as defined in claim 6, wherein:

the measurement volume is defined in part by an end wall;

the calibration objects are pins; and

the method further includes a step of attaching the pins to predetermined locations on the end wall.

8. A method as defined in claim 6, wherein:

the steps of modulating, scanning, detecting

and comparing are completed before the step of modulating and repeating is initiated;

the initial step of scanning includes a final step of scanning the modulated beam across the calibration objects; and

the step of scanning during the step of modulating and repeating includes an initial step of scanning the modulated beam across the calibration objects.

9. A method as defined in claim 1, wherein the step of comparing includes the steps of:

comparing the detection signal with the modulation signal in a first phase detector, to generate a first signal;

delaying the modulation signal by a predetermined amount;

comparing the detection signal with the delayed modulation signal in a second phase detector, to generate a second signal; and

selecting the phase difference signal to be either the first signal or the second signal.

10. A method as defined in claim 1, wherein the step of processing includes a step of processing the first and second phase difference signals and the detection signal to determine the three-dimensional shape of the article's exterior surface.

11. A method for determining the three-dimensional shape of an article located within a measurement volume, comprising the steps of:

scanning a first modulated beam of coherent radiation across an article located within a measurement volume such that the beam is reflected from the article to produce a first reflected beam;

detecting the intensity of the first reflected beam to generate a first detection signal;

comparing the phase of the first detection signal with the phase of the first modulated beam and generating a first phase difference signal indicative of the article's coarse position;

scanning a second modulated beam of coherent radiation across the article such that the beam is reflected from the article to produce a second reflected beam;

detecting the intensity of the second reflected beam to generate a second detection signal;

comparing the phase of the second detection signal with the phase of the second modulated beam and generating a second phase difference signal indicative of the article's fine position; and

processing the first and second phase difference signals to determine the three-dimensional shape of the article's exterior surface.

12. A method as defined in claim 11, wherein:

the step of scanning the first modulated beam includes a step of modulating the beam's intensity in accordance with a first modulation signal that is a sine wave having a first frequency; and

the step of scanning the second modulated beam includes a step of modulating the beam's intensity in accordance with a second modulation signal that is a sine wave having a second frequency.

13. A method as defined in claim 11, wherein the steps of scanning, detecting and comparing the first modulated beam are completed before the steps of scanning, detecting and comparing the second modulated beam are initiated.

14. A method as defined in claim 11, wherein:

a plurality of calibration objects are located within the measurement volume, the calibration objects having known positions in three dimensions; and

the step of processing includes a step of calibrating the first and second phase difference signals based on the portions of such signals that are derived from scanning the first and second modulated beams across the calibration objects.

15. A method as defined in claim 14 wherein:

the steps of scanning, detecting and comparing the first modulated beam are completed before the steps of scanning, detecting and comparing the second modulated beam are initiated;

the step of scanning the first modulated beam includes a final step of scanning the first modulated beam across the calibration objects; and

the step of scanning the second modulated beam includes an initial step of scanning the second modulated beam across the calibration objects.

16. Apparatus for determining the three-dimensional shape of an article located within a measurement volume, comprising the steps of:

a modulator for modulating the intensity of a beam of coherent radiation in accordance with both a first modulation signal and a second modulation signal;

a scanner for scanning the modulated beam across an article located within a measurement volume such that the beam is reflected from the article to produce a reflected beam;

a detector for detecting the intensity of the reflected beam to generate a detection signal;

a phase comparator for comparing the phase of the detection signal with the phase of the first modulation signal and with the phase of the second modulation signal and for generating a first phase difference signal and a second phase difference signal, respectively; and

a processor for processing the first and second phase difference signals to determine the three-

dimensional shape of the article's exterior surface.

17. Apparatus as defined in claim 16, wherein:

the first modulation signal is a sine wave having a first frequency; and

the second modulation signal is a sine wave having a second frequency.

18. Apparatus as defined in claim 16, wherein:

the measurement volume is stationary; and

the scanner includes a movable mirror for scanning the modulated beam along a first direction and a transporter for moving the mirror in a second direction relative to the measurement volume, such that a raster scan of the measurement volume is achieved.

19. Apparatus as defined in claim 16, wherein:

the apparatus further includes a plurality of calibration objects located within the measurement volume, the calibration objects having known positions in three dimensions; and

the processor is configured to calibrate the first and second phase difference signals based on the portions of such signals that are derived from scanning the modulated beam across the calibration objects.

20. Apparatus as defined in claim 19, wherein:

the measurement volume is defined in part by an end wall; and

the calibration objects are pins secured at predetermined locations on the end wall.

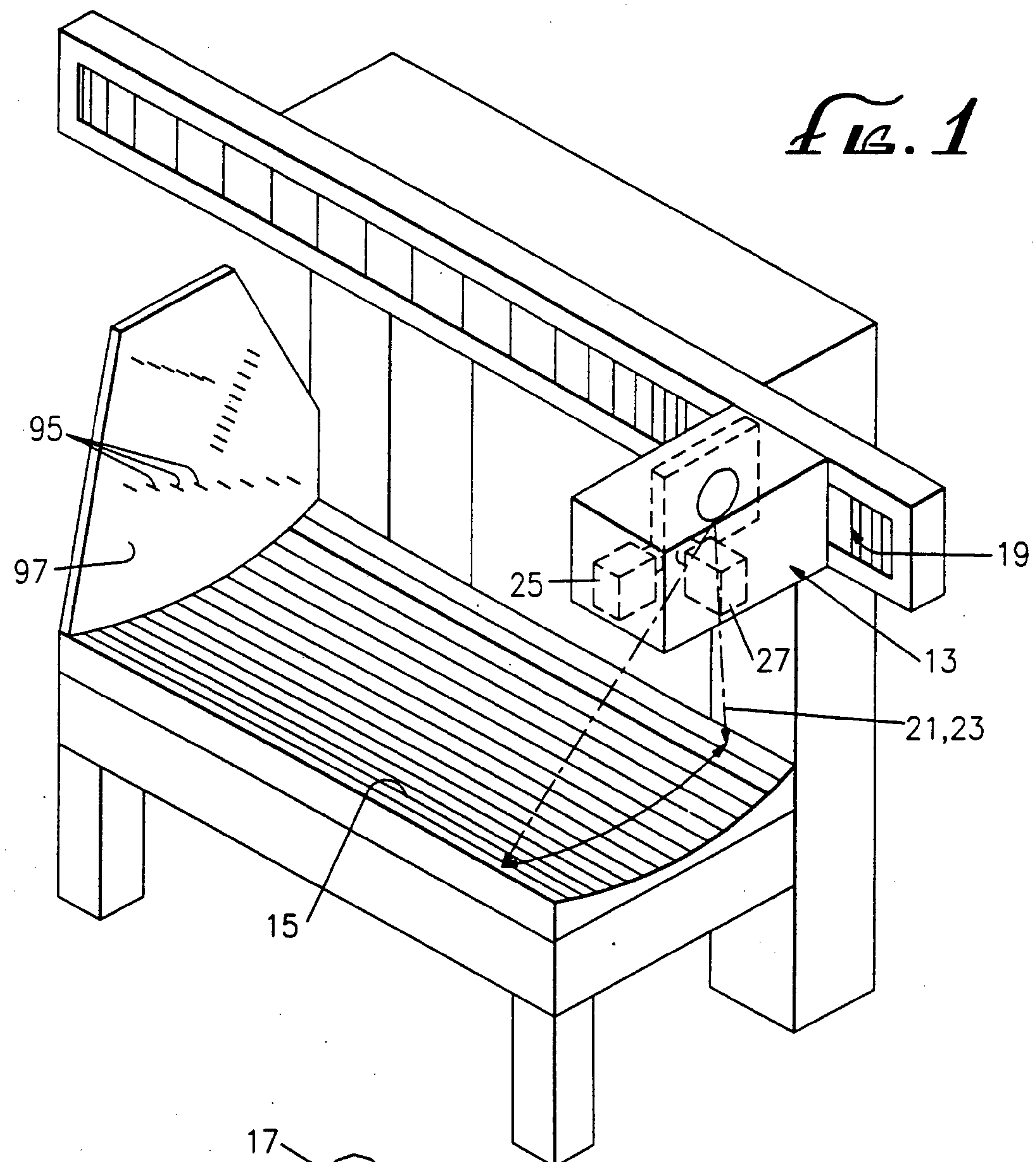


FIG. 1

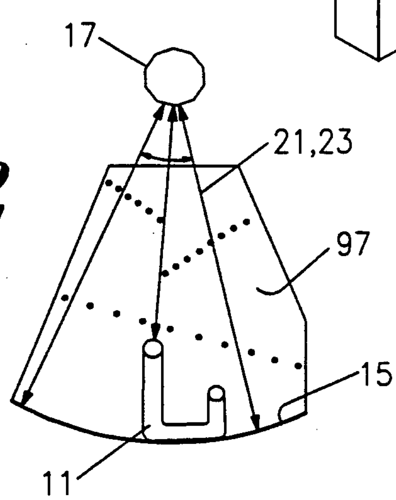


FIG. 2

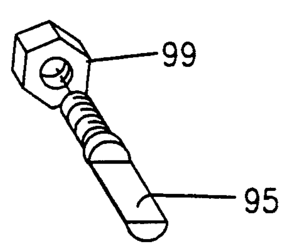


FIG. 7

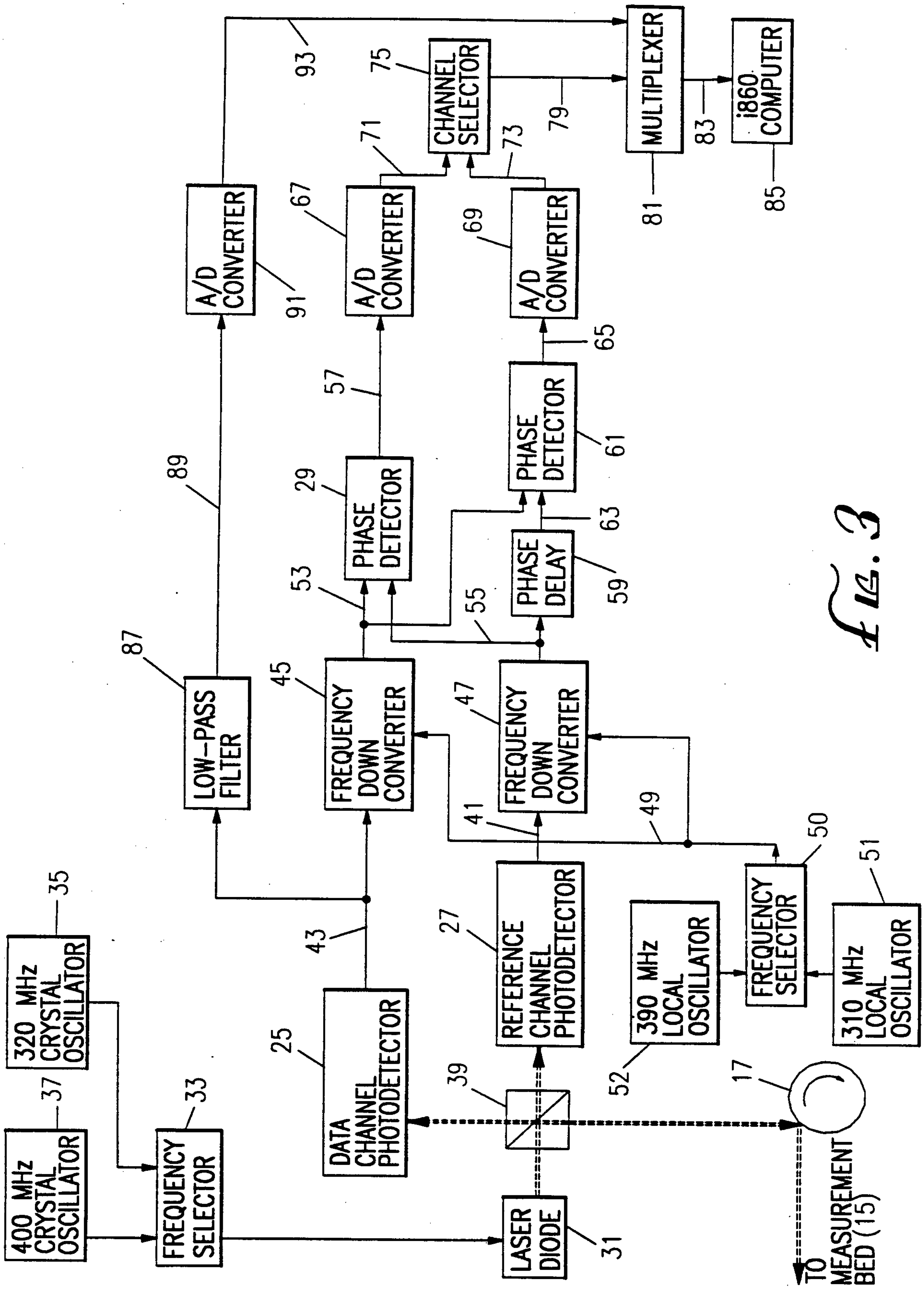

400 MHz CRYSTAL OSCILLATOR
320 MHz CRYSTAL OSCILLATOR
37
35
FREQUENCY SELECTOR
33
LASER DIODE
31
DATA CHANNEL PHOTODETECTOR
25
39
TO MEASUREMENT BED (15)
17
REFERENCE CHANNEL PHOTODETECTOR
27
390 MHz LOCAL OSCILLATOR
52
FREQUENCY SELECTOR
50
310 MHz LOCAL OSCILLATOR
51
43
41
49
LOW-PASS FILTER
87
FREQUENCY DOWN CONVERTER
45
FREQUENCY DOWN CONVERTER
47
53
55
PHASE DETECTOR
29
PHASE DELAY
59
63
PHASE DETECTOR
61
89
57
65
A/D CONVERTER
91
A/D CONVERTER
67
A/D CONVERTER
69
71
73
CHANNEL SELECTOR
75
79
93
MULTIPLEXER
81
83
i860 COMPUTER
85

FIG. 3

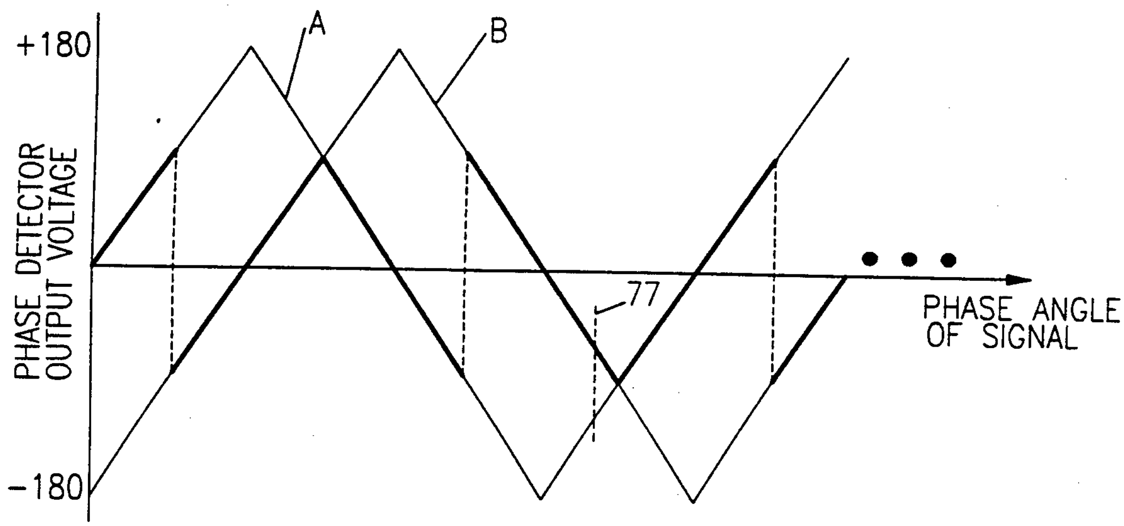

+180
-180
A
B
PHASE DETECTOR OUTPUT VOLTAGE
77
PHASE ANGLE OF SIGNAL

FIG. 4

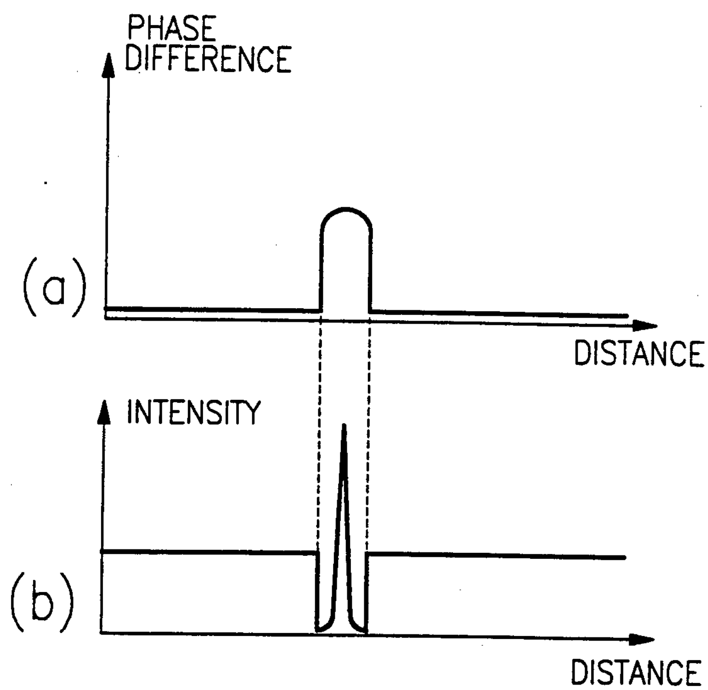
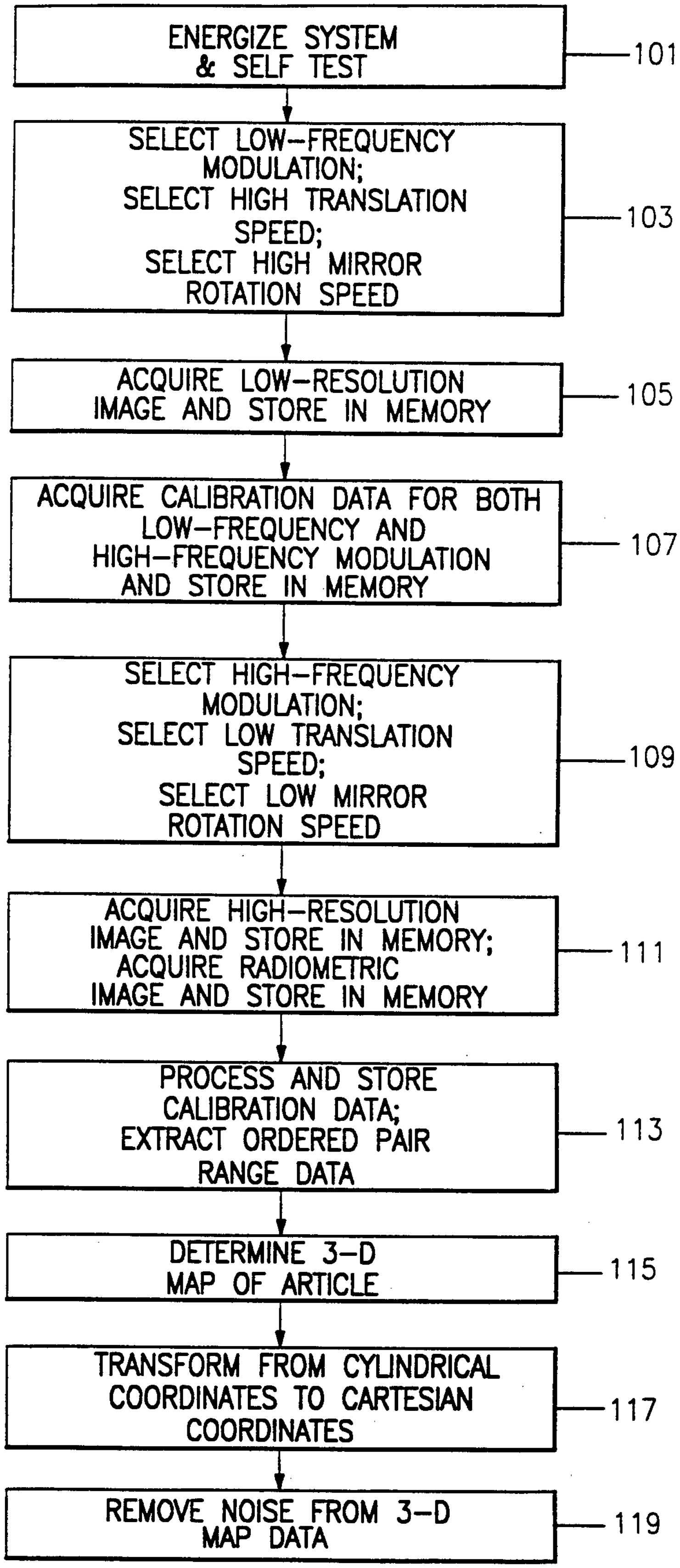

PHASE DIFFERENCE
(a)
DISTANCE
INTENSITY
(b)
DISTANCE

FIG. 5

FIG. 6


ENERGIZE SYSTEM & SELF TEST
101
SELECT LOW-FREQUENCY MODULATION; SELECT HIGH TRANSLATION SPEED; SELECT HIGH MIRROR ROTATION SPEED
103
ACQUIRE LOW-RESOLUTION IMAGE AND STORE IN MEMORY
105
ACQUIRE CALIBRATION DATA FOR BOTH LOW-FREQUENCY AND HIGH-FREQUENCY MODULATION AND STORE IN MEMORY
107
SELECT HIGH-FREQUENCY MODULATION; SELECT LOW TRANSLATION SPEED; SELECT LOW MIRROR ROTATION SPEED
109
ACQUIRE HIGH-RESOLUTION IMAGE AND STORE IN MEMORY; ACQUIRE RADIOMETRIC IMAGE AND STORE IN MEMORY
111
PROCESS AND STORE CALIBRATION DATA; EXTRACT ORDERED PAIR RANGE DATA
113
DETERMINE 3-D MAP OF ARTICLE
115
TRANSFORM FROM CYLINDRICAL COORDINATES TO CARTESIAN COORDINATES
117
REMOVE NOISE FROM 3-D MAP DATA
119

INTERNATIONAL SEARCH REPORT

Inter nal Application No
PCT/US 94/12447

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01B11/24

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y A	EP,A,0 192 993 (KAPPNER) 3 September 1985 see column 3, line 12 - column 5, line 28; figures ---	1 2,6
Y	GB,A,2 142 427 (CITIZEN WATCH) 16 January 1985 see abstract; figures ---	1
Y A	VDI ZEITSCHRIFT, vol.134, no.9, September 1992, DUSSELDORF DE pages 18 - 22 VON GUNTHER PRITSCHOW E.A. 'VOM DESIGNOBJEKT IN DIE FERIGIUNG: SCHNELLER MIT 4D-LASERMESSSYSTEMEN' see the whole document --- -/--	1 4,10

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

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Date of the actual completion of the international search	Date of mailing of the international search report
13 February 1995	08.03.95

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Ramboer, P

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INTERNATIONAL SEARCH REPORT

Inte nal Application No
PCT/US 94/12447

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	PATENT ABSTRACTS OF JAPAN vol. 12, no. 354 (P-761) 22 September 1988 & JP,A,63 108 208 (NIPPON AIR BRAKE) 13 May 1988 see abstract ---	1
A	PATENT ABSTRACTS OF JAPAN vol. 9, no. 76 (P-346) 5 April 1985 & JP,A,59 206 706 (YOUJI WADA) 22 November 1984 see abstract -----	1

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 94/12447

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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GB-A-2142427	16-01-85	JP-C- 1680549	13-07-92
		JP-B- 3044243	05-07-91
		JP-A- 59214706	04-12-84
		JP-A- 59216008	06-12-84
		US-A- 4577967	25-03-86